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Mean Annual Mid-Latitude Moisture Profiles to 31 Km

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Abstract

Average yearly vertical profiles up to 31 km for middle latitude, derived independently, for mixing ratio and moisture dewpoint-frostpoint, are presented. Since the relation between mixing ratio and frostpoint is non-linear, other moisture expressions were derived from each of the two basic profiles, using Standard Atmosphere conditions. Up to 7 km (400 mb), the profiles were derived by an indirect approach; conventional radiosonde humidity measurements were utilized. Above that level the profiles are based upon selected experimental humidity ascents, subjectively selected and weighted. The mixing ratio profile decreases from 6,150 parts per million at the surface to 9 ppm at 16 km then increases slightly with height; the surface dewpoint is taken as 4 °C, decreasing to -78 °C at 18 km, then increasing to -71 °C at 31 km.

Contents

Figures

Tables

Symbols

Symbol	Meaning	Units used herein
R	Density of air or of water vapor	g/m^3 or mg/m^3
T	Temperature	°C
P	Pressure	mb
e	Vapor pressure	microbars (μb) = 10^{-3}mb
W	Precipitable water	microns (μ) = 10^{-4}cm
w	Mixing ratio	mg/kg or parts per million (ppm)
U	Relative humidity	percent
H	Altitude	geopotential km

Subscripts

d	Dewpoint
f	Frostpoint
s	at saturation
v	at actual vapor concentration

Additional Notation

A symbol followed by a prime (') indicates derivation from the mean dewpoint or frostpoint, rather than from mean mixing ratio. A bar above a symbol indicates a mean value.

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1. PURPOSE

This study offers preliminary models of the variation with height of atmospheric moisture, similar in concept to that of other standard atmospheres. Standard atmospheres were developed primarily as a realistic reference for the standardization of aircraft instruments and performance standards. The first models were relatively crude, but as the needs of the aircraft and associated industries increased, and as atmospheric data became more plentiful, model atmospheres were revised, refined, and extended to higher altitudes. For example, the U. S. Committee on Extension of the Standard Atmosphere (COESA) is sponsoring Supplemental Atmospheres for every 15° latitude for summer and winter.

Basic elements of the Standard Atmosphere are temperature and pressure as functions of altitude; from them, virtually every other desired element, such as density, mean free path, molecular weight, etc., can be computed. With the exception of low-level relative humidity data used in some atmospheres for virtual temperature computations, the variation with altitude of any moisture parameter is not mentioned in any published model atmosphere, yet scientists and designers engaged in the atmospheric radiation field have a pressing need for such information.

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To satisfy these needs, two independent moisture profiles have been developed from the available data which, after thorough evaluation, appeared reliable; one profile is for mixing ratio, the other for dewpoint and frostpoint. Because the relation between mixing ratio and dewpoint-frostpoint is not linear, these two sets of moisture measure differ significantly. Each is based on observations reported in, or converted to, appropriate units. In addition, other measures of moisture (precipitable water, absolute humidity, vapor density, relative humidity) have been derived from each of the two basic representations.

The paucity and ambiguity of upper-air moisture data make the models offered here quite crude, and limit them to the middle latitudes (35° to 55°) of the Northern Hemisphere; no stratospheric moisture measurements are available as yet for the Southern Hemisphere. The models are restricted to average yearly values, and extend only to 31 km, the upper limit of observation. As observations increase, the models can be revised, refined, and extended, to evolve in the same way as other representations of atmospheric structure.

2. INSTRUMENTS

Routine upper-air measurement of temperatures, pressures, and humidities are made by radiosonde. The humidity measurements are the least accurate of all these, and are the most limited in vertical extent. Many different humidity elements have been used at one time or another in radiosondes (hair, goldbeater's skin, lithium chloride, carbon element, etc.), but none has yet proven entirely satisfactory. The lithium chloride strip in the current U. S. radiosonde ceases to function at temperatures below -40°C or, when the relative humidity is very low.

Estimates of relative humidity called "statistical values" are recorded when the hygrometer is below its operating range. For example, when the humidity element causes "motorboating" at 12° to 40°C, a statistical value of 12 % is recorded in parentheses on the appropriate form (Air Weather Service 1961);[1] but on punch cards for machine tabulations, the statistical value is used without such notation, and the machine tabulations include these estimated values. All the conventional radiosonde humidity data used in this report were machine tabulated from radiosondes utilizing a lithium chloride humidity element; hence, they contain the aforementioned errors.

More than half the humidities reported at 400 and 300 mb at 12 representative stations, from Anchorage to Miami, during the five years, 1956-1960, were such "statistical" values. Maximum, average, and minimum percentages of estimated values as listed in an unpublished Weather Bureau tabulation were:

Level (mb)	850	700	500	400	300
Maximum	21	40	53	58	78
Average	8	15	39	50	60
Minimum	3	9	28	36	52

Temperature limitations preclude radiosonde humidity data at altitudes higher than 9 km in the mid-latitudes. In fact, most summarized data extend only as high as 400 mb (7 km). At higher altitudes, present knowledge of humidity has been obtained from experimental ascents utilizing special humidity-measuring equipment. Of all the many instrument or methods used to obtain high-altitude humidity values, all but three have either been proven unreliable or are still in the developmental stage. Any system may be subject to possible contamination of the air sample by water vapor carried aloft by the balloon, aircraft, or instrument.

2.1 Direct Measurement of the Frost Point

Direct measurement of the frostpoint has been by far the most common method of measuring stratospheric humidity. The frostpoint hygrometer consists of a polished plate cooled by a refrigerating system until frost occurs, a sensing device to detect the frost formation, stop the refrigeration and start a heating element to melt the frost, and a temperature-measuring device (thermistor) embedded in the plate. Thus the device "hunts" for the temperature at which frost first occurs, and measures the frostpoint (T_f) directly.

The frostpoint hygrometer has several variations. An aircraft-mounted, manually-operated, model is used extensively in England, while balloon-borne automatic (telemetering) devices have been used almost exclusively in the U. S. and Japan.

The frostpoint hygrometer has been much critized for possible inadequate cooling power of the refrigeration system, overcompensation by the heating coil, inadequate ventilation of the instrument, etc. The instrument has undergone considerable modification to eliminate some of the objectionable features, and continues to be the most common method of measuring stratospheric moisture.

2.2 Attenuation of Radiation by Water Vapor

Attenuation of radiation by water vapor is measured by coupling a sun-seeker with a spectrometer flown on a balloon (aircraft platforms have occasionally been used). From measurement of the infrared solar spectrum, the amount of water between the spectrometer and the sun can be deduced. To obtain a vertical moisture profile, several observations must be made on each ascent. The accuracy of the infrared absorption measurements has not been questioned but the results of such measurements are somewhat subjective (Murcray, et al. 1961)[19] because:

a. Absorption by the water vapor in the path is a function of the temperature and pressure and, thus, depends on their vertical structure above peak altitude; this structure must be assumed by the analyst.

b. The selection of the absorption laws to be used in calculating the amount of water vapor is not clear-cut but depends on the judgement of the analyst.

2.3 Collection of Water Vapor by a Filter

Collection of water vapor by a filter is done by devices carried aloft to the predetermined altitude by balloon. A known amount of air passes through an efficient collector that removes all of the water vapor. The instrument is then cut loose, recovered, and analyzed quantitatively for water so that the mixing ratio (w) is measure directly.

These absorption devices generally are considered by most investigators to be the most accurate of all stratospheric humidity measuring devices. Unfortunately, such devices do not give vertical profiles. In theory, profiles can be obtained by suspending a number of devices from the same balloon to sample at a number of levels; in practice, the number of devices is severely limited by the payload capacity of the balloon. Alternatively, a number of balloons could be released simultaneously to sample at different levels, but this approach is also beset with technical difficulties. To date, only single altitude samples have been made. Two different instruments utilizing this principle have been used:

a. A "Nitrogen - Cooled Vapor Trap" designed for and flown by the United Kingdom Atomic Energy Authority (UKAEA). In this device the water vapor and CO_2 are frozen out when the air passes through a trap cooled with liquid nitrogen. Since the ratio of CO_2 to air is constant to altitudes far above 30 km, the total amount of ingested air can be deduced by measuring the amount of CO_2 in the trap (Barclay, et al. 1960;[3] Brown, et al. 1961).[6]

b. In the "Molecular Sieve," flown by General Mills, Inc., the absorber is a chemical (zeolite) which traps the water vapor as well as CO_2. The air passing through the zeolite filter is metered and a CO_2 determination is also made, thus giving a double check on the amount of ingested air. (Steinberg and Rohrbough 1961).[26]

3. MEASUREMENTS

Available humidity data can be classified conveniently into two general classes: up to 400 mb (about 7 km) and from that point to 10 mb (31 km). In this study the average elevation of annual mid-latitude tropopause has been taken as 11 km, in accordance with the Standard Atmosphere; elevations above 11 km will be referred to as stratospheric, and below, tropospheric.

Up to 400 mb, where the conventional radiosonde humidity element often functions, a veritable wealth of data exists, except over oceans and sparsely populated regions. Summaries of radiosonde ascents are published as part of the official publication of various weather services. A reasonably good world-wide sample of data is also published by the U. S. Weather Bureau for WMO as part of the CLIMAT reports (Monthly Climatic Data for the World). Low-level humidity data are so plentiful that world-wide maps have appeared for the mid-seasonal months giving the amount of precipitable water above the surface and above 850, 700, and 500 mb levels (Bannon and Steele 1960)[2]. However, when the temperature was low and the water vapor content at 300 mb was not measured (as is often the case), it was assumed to be zero. Monthly and annual maps of the average precipitable water from the surface to 325 mb over the U. S. also are available (Reitan 1960)[22]. In these, also, precipitable water was assumed to be zero at temperatures of -40°C and lower; however, at 350 mb the "motorboating" value was used for the appropriate temperature when the relative humidity was missing at that level.

Moisture data are extremely scarce above 400 mb compared to the lower levels. With two exceptions, all stratospheric moisture measurements have been taken nonsystematically by individuals and/or organizations interested in the field. These ascents were made sporadically whenever the time, location, funds, etc., were available. Less than 50 such stratospheric ascents have succeeded, and less than 10 reached or exceeded 31 km. Table 1 lists the instruments, principal investigators, and organizations making these nonsystematic stratospheric moisture ascents yielding discrete moisture data at given pressures or altitudes.

Table 1
Instruments, investigators, and organizations responsible for nonsystematic stratospheric humidity measurements.

INSTRUMENT	REFERENCE	ORGANIZATION
Automatic frostpoint hygrometer	E. W. Barrett, L. R. Herndon and A. J. Carter (1950)[4]	Univ. of Chicago
Hygristor	C. J. Brasefield (1954)[5]	USA Signal Corps
Vapor trap	F. R. Barclay, M. J. Eliot, P. Goldsmith, J. V. Jelly, (1960),[3] F. Brown, H. F. Green, A. G. Parham (1961)[6]	United Kingdom Atomic Energy Authority (UKAEA)
Automatic frostpoint hygrometer	J. A. Brown and E. G. Pybus (1960)[8]	USA Ballistic Research Laboratories (BRL)
Automatic frostpoint hygrometer	H. J. Mastenbrook, J. E. Dinger (1960, 1961)[17, 18]	USN Research Laboratory (NRL)
Infrared spectrometer and automatic frost-point hygrometer	D. C. Murcray, F. H. Murcray W. J. Williams (1961)[19]	Univ. of Denver (U of D)
Automatic frostpoint hygrometer, aircraft-borne	T. W. Caless (1961)[9]	Bendix Aviation Corp.
Molecular sieve	S. S. Steinberg and S. F. Rohrbough (1961)[26]	General Mills, Inc.

Two sets of more or less systematic probes of stratospheric humidity conditions have been made. The British Meteorological Research Flights (MRF) used manually operated frostpoint hygrometers; maximum altitude reached by the aircraft were about 125 mb (15 km). Most ascents were over southern England (Tucker 1957),[27] but some were as far away as northern Norway (Brewer 1955)[7] and Kenya (Kerley 1961).[15] Nearly 400 ascents over southern England, well distributed throughout the year, reached or exceeded 9 km.

In its IGY program, the Japenese Meteorological Agency (JMA) utilized balloon-borne automatic frostpoint hygrometers (JMA 1960) during September and December, 1957; and March, June, September, and December, 1958, at Sapporo (43N, 141E), Tateno (36N, 140E), Hachijoshima (33N; 140E), and Kagoshima (32N, 131E). On several occasions two ascents were made in one day; on some days soundings were made at two or more stations simultaneously. About 100 ascents reached 300 mbs; 2 ascents, 10 mbs (31 km).

4. DISCUSSION

The first systematic measurements of stratospheric humidity, by the MRF indicated frostpoints of -80 to -85°C, giving mixing ratios around 2 mg/kg (parts per million) at 14 to 15 km, with no apparent seasonal or geographical variation. This constancy, and the general dryness, were not substantiated by other ascents in the United States, or by the JMA flights. No tenable theory of atmospheric circulation can explain all such observations (Gutnick 1960;[12] Sissenwine and Gutnick 1960;[24] Greenfield and Kellogg 1960;[11] Gutnick 1961[13]).

However, one feature of the stratospheric moisture regime is rapidly gaining wide acceptance among scientists in the field: the structure of the mixing-ratio profile. Recent humidity ascents show a decrease in mixing ratio with altitude to a minimum value several kilometers above the tropopause, the exact altitude differing from ascent to ascent. Above this point the mixing ratio increases to at least 32 km, the highest altitude to which analysis could be extended. As yet no noncontroversial tenable theory has been advanced to explain the physical mechanism involved.

How should an average stratospheric moisture profile be constructed? Some authorities advocate use of only those data which are considered reliable. But experts do not agree which data are reliable (Gutnick 1961).[13] Any profile based on such selection must, of necessity, be subjective. It will, to a great extent, reflect the opinions, prejudices, and experience of the selector.

Despite these limitations, the present state-of-the-art renders this approach the only logical method for obtaining a moisture profile. Indiscriminate use of available data (some of which are doubtless in error) would yield a meaningless hodgepodge profile.

The stratosphere moisture profiles presented here are based on those stratospheric moisture ascents which promised the most valid results. Thus the moisture profiles in the stratosphere are subjective educated guesses. A valid annual profile of any atmospheric parameter must be:

a. Representative of all months or seasons;
b. Representative of the climatic types comprising the selected area;
c. Based on an unbiased sample, i. e. the selected sample must represent average conditions and not some unusual year or years.
d. Physically consistent with know information, e. g. at any altitude, the mean dewpoint cannot be warmer than the mean temperature.

The paucity and/or reliability of stratospheric humidity data are such that the only condition that could be objectively satisfied was that of physical validity ("d").

Since the nonsystematic data were too few in number and too sporadic in time and space to give general conclusions, only the systematic ascents (JMA and MRF) could be used for this type of analysis.

In all JMA ascents a conventional radiosonde and a frostpoint hygrometer were flown simultaneously. The standard elements (temperature, height, relative humidity) were obtained (when available) from the radiosonde at all standard levels between 1000 mb and 10 mb. The only elements recorded or derived from the frostpoint hygrometer were temperature, dewpoint, and relative humidity. To give equal weight to each day, all pairs of twice-a-day ascents for each station were averaged as one observation. For each ascent the frostpoint and mixing ratio were recorded for every standard level above 400 mb. For Tateno only the 700, 500, and 100 - mb temperatures, and the dewpoints from both instruments at the 500, and 700 - mb levels, were extracted. Stratospheric moisture content in the JMA data, unlike that indicated by the MRF data, was extremely variable (Tables 2 and 3).

5. BIAS

To seek general conclusions on seasonal or spatial variations, the moisture data for all four JMA stations were combined into two categories: June and September (warm), December and March (cold). Although the MRF ascents indicated no seasonal variation in the lower stratosphere, the JMA mean mixing ratios for the warm and cold seasons differ by an average of 15 mg/kg at each stratospheric level; the maximum difference was 49 mg/kg. Mixing ratios ranged from 1 to 138 mg/kg at 200 mb, and from 1 to 84 mg/kg at 80 mb in the warm season; from 4 to 65 mg/kg at 200 mb, and 2 to 96 mg/kg at 80 mb in the cold months.

The MRF ascents showed the moisture content of the lower stratosphere was similar for all geographic areas and climatic regimes, but the means of the MRF ascents are among the driest and the mean JMA ascent the wettest on record, in terms of mixing ratio.

This conflict between the JMA and MRF data precluded any firm decision on seasonal or geographical variations. The most conservative approach was to assume both seasonal and geographic variation. Thus the sample selected for analysis should, as nearly as possible, run the gamut of geographic areas and represent an average of all seasons in the desired area, i. e. middle latitudes.

Both the MRF and JMA data were tested for possible bias by comparing long-period (climatological) records of elements with those measured on the hygrometric ascents. Mean annual temperatures at the 700, 500 and 200 - mb levels from the MRF ascents were compared to the climatological means at Larkhill (southern England) while the annual temperatures from the JMA ascents (mean of December, March, June and September) for Tateno at 700, 500 and 100 mb were compared to the long-term Tateno mean (Goldie, Moore, and Austin 1958):[10]

Pressure surface, mb		700	500	200	100
England	(MRF	-4	-21	-55	-
	(Larkhill mean	-4	-20	-56	-
Japan	(JMA Flights	-1	-15	-	-62
	(Tateno mean	0	-14	-	-61

Table 2. Mixing ratios in mg/kg (parts per million) at 80 mb over Tateno (T), Sapporo (S), Hachijoshima (H), and Kagoshima (K), Japan, derived from dewpoints rounded to nearest degree.

DATE	SEP 1957				DEC 1957				MAR 1958				JUNE 1958				S[illegible] 1958				DEC 1958			
	T	S	H	K	T	S	H	K	T	S	H	K	T	S	H	K	T	S	H	K	T	S	H	K
12							3														9			
13						9											4					15		8
14					8												4				15			
15					15									4							6	64		11
16													5	20			1	6			15	13		
17						32							3									11	4[illegible]	
18						24			9					2						3	13			
19						48		15	64				15	24			4	11			4	6		
20									24				15			2				3		96		8
21	2									36			11							3		4		7
22		17													8		11	27						
23	11	84	4						16			2	4											
24	17	13	2						4					48										
25	24		4							11														
26	1	3	3							56														
Mean	11	29	3	-	12	32	3	15	23	34	-	2	8	20	8	2	5	15	-	3	10	30	48	8

Table 3. Mixing ratios in mg/kg (parts per million) at 200 mb over Tateno (T), Sapporo (S), Hachijoshima (H), and Kagoshima (K), Japan, derived from dewpoints rounded to nearest degree.

	SEP 1957				DEC 1957				MAR 1958				JUNE 1958				SEP 1958				DEC 1958			
DATE	T	S	H	K	T	S	H	K	T	S	H	K	T	S	H	K	T	S	H	K	T	S	H	K
12							13														8			
13						11											65					8		38
14					6												50				15			34
15					17			26						11		38	74					17		35
16					19	13		15					65	17			19	22			17	4		
17						9		7			57		57								9	4	34	
18						13			26					15						95	26			34
19			38					19	19				34	15			26	57			8	15		
20										6			29			9	34			22	13	65		26
21	44								13	29			29						65	19	13	8		13
22	15	29	38												44		74	74	1	74				43
23	44	22	138						11			50	17		22									
24	5	13	29						13					44										
25	29	7	44							17														
26	74	26	57							19														
Mean	35	29	57	-	14	12	13	16	16	18	57	50	38	20	33	24	49	51	33	52	14	17	34	32

The excellent agreement suggests that the samples are representative, and that combining December, March, June, and September for the JMA ascents to yield an annual value is probably valid.

Virtually every stratospheric moisture ascent is biased to some degree. Most balloons are launched only when the surface wind speeds are low; and, because there is danger of water contamination to the instrument, hygrometric ascents are limited to rainless days. The vapor trap was flown in England (Brown, Goldsmith, Green, Holt, and Parham 1961)[6] only with light surface winds, clear skies, and a vertical wind profile such that the balloon was not carried over the sea. Such conditions occur simultaneously on only a few days in spring and summer.

6. TROPOSPHERE

The most obvious and direct method for obtaining the vertical moisture distribution in the troposphere would be to map the appropriate radiosonde data on a world-wide basis, then pick off values at grid points, or planimeter the maps to give the desired result. This direct approach would be extremely costly and time-consuming for relatively small-pressure increments (about every 50 mb), since most published radiosonde data are only for the standard levels (surface 850, 700, 500, etc.).

A simple alternate method was devised, using recently published world-wide maps (Bannon and Steel 1960)[2] of precipitable water above the surface, above 850 mb, above 700 mb and above 500 mb (in practice the above refers to an upper limit of 300 mb). Averaging the mid-seasonal months at grid points, for, say 45°N, gave the mean annual precipitable water at latitude 45°N, above each of the levels. But the mixing ratios or dewpoints used to construct the precipitable water maps could not be rederived. However, a station (or several stations) having closely similar precipitable water values for the same layers should exhibit vertical distributions of mixing ratios and dewpoints representative of the respective mean annual values for 45°N. Although any one of an infinite number of mixing-ratio combinations will yield the same precipitable water value above one level; for all practical purposes, only one vertical distribution will yield similar precipitable water values above four widely-separated surfaces, especially if the mixing ratios must decrease with altitude in the troposphere.

Thus in practice two stations having the same amount of precipitable water from the surface, 850, 700, and 500 mb to 300 mb, and their mixing ratio decreasing with height, almost certainly have similar vertical distribution of mixing ratios and dewpoints.

From the data of Reitan (1960)[21] and other available material, the search for typical stations was narrowed down to several possible choices. The final selection was mean of Fukuoka, Japan, (33° 35' N, 130° 27' E) for January and October, and Washington, D. C., (38° 50' N, 72° 02' W) for April.

The mean annual precipitable water (cm) from the various levels to 300 mb, as derived from the maps of Bannon and Steele for 45°N and obtained from the mean of Fukuoka (January and October) and Washington, D. C., (April) was:

Level (mb)	SFC	850	700	500
From maps at 45°N	1.6	0.9	0.4	0.1
Fukuoka + Washington	1.6	0.9	0.4	0.09

Mixing ratios and dewpoints for Fukuoka and Washington were machine-tabulated at 50 mb increments from the surface to 400 mb and were used to derive the moisture profiles, as described later.

7. STRATOSPHERE

Selection of the most suitable stratospheric moisture ascents from the available data was indeed a vexing problem, for lack of established criteria or standards. The various groups making stratospheric moisture ascents were requested to select one or more best ascents. Some had already given evaluations in print, and others had utilized instrumentation now known to be faulty. No sounding was used which showed any internal inconsistencies (super-saturated layers) or malfunction during ascent.

Stratospheric moisture soundings utilized in construction of the moisture profile were:

a. Three NRL profiles of 8 February 1960, 8 April 1960, 27 June 1960 were selected (Mastenbrook and Dinger 1960, 1961). All were taken at the NRL Chesapeake Bay Annex (CBA) some 40 miles southeast of Washington, D. C.; very long load lines (900 ft) were used to minimize possible contamination from the balloon. The investigators placed greatest confidence in the latest two flights (27 June and 8 April) primarily because of the excellent agreement between ascent and descent. Actually, such agreement is a two-edged sword; while it is doubtless a good test of the repeatability of the hygrometer, agreement between ascent and descent may indicate a static weather situation; thus, use of such data exclusively may lead to a highly biased result (Gutnick 1961).[13] The investigators also felt that the 8 February flight provided representative results during descent (all of the NRL data used in this study were descent data).

b. Two Ballistic Research Laboratory (BRL) ascents, on 3 April 1960 at Aberdeen, Md. (unpublished) and 29 April 1960 at Ft. Monmouth, N. J. (Marks 1960),[16] were selected by Brown and Pybus from their extensive series of nonsystematic moisture ascents, many as yet unpublished, from the Arctic to the Antarctic.

c. Two University of Denver ascents were chosen, an infrared spectrometer flight on 18 April 1960 and a hygrometric ascent on 1 March 1961, both at Holloman Air Force Base, Alamogordo, N. M. The spectrometer ascent (Murcray, Murcray and Williams 1961)[19] was the only one of its kind having enough points for a complete profile to be constructed to 26 km; the assumptions used in its computation appear reasonable and the shape of the mixing ratio profile agrees with that generally accepted. The hygrometric ascent (unpublished) was described in a letter from D. Murcray as having been made on the same balloon with a spectrometer:

"The sun-seeker didn't work very well and we only got spectra up to about 40,000 feet. The frostpoint instrument worked very well, and we got what we think are reliable measurements of the frostpoint. We monitored the temperature continually and also periodically heated the mirror to make sure the frost was removed and let the mirror return to the frostpoint. The servo system appeared to be working very well, and the system set at a definite value with none of the oscillation we had noted when we flew the instrument on other occasions." Subsequent check of the data indicated that calibrations were accurate.

d. The UKAEA nitrogen-cooled vapor trap was flown seven times in the spring or summer of 1958, 1959, and 1960, over southern England (Brown, et al. 1961).[6] Samples were taken at elevations ranging from 24.4 to 30.2 km (mean height 27.5 km), with special precautions to prevent or check against contamination. By "spiking" the hydrogen in the balloon with deuterium, water vapor diffusion through the balloon skin was shown to be unimportant.

e. One of the three General Mills' molecular sieve ascents was used, that of 15 March 1961, when two units were flown at San Angelo, Texas. One malfunctioned; on the other the amount of ingested air at 21.9 km measured by the flow meter agreed with the CO_2 determination. The first flight had been unsuccessful.

f. The JMA data had been carefully screened before publication (JMA 1960).[14] Ascents on which the heating coil circuit gave trouble and those which indicated supersaturation were rejected. The mean absolute differences between dewpoints of the conventional radiosonde and the frostpoint hygrometer at the 700 and 500 mb level were within the range of radiosonde error.

g. The large number of MRF ascents, the high scientific calibre of the personnel taking the observations, and the carefully-tested instrumentation made their inclusion a virtual necessity.

All stratospheric moisture ascents used in this study are presented in Figures 1 and 2. In both figures, the abscissa is mixing ratio, on a logarithmic scale; the ordinate is height in kilometers. On the right, an auxiliary scale gives the pressure corresponding to height in the revised U. S. Standard Atmosphere, because most of the basic data were given in terms of mixing ratios at certain pressures, not heights; only the University of Denver hygrometric and spectrographic flights, and the molecular sieve and vapor trap results, had been published as mixing ratios with respect to height.

Use of a single Standard Atmosphere relation to convert the various ascents to a common height basis leads to only negligible error. Because pressure decreases logarithmically with height, the percentage variation in the height of a pressure surface is much less than the percentage variation in the pressure at a fixed height. For example, at 45°N, the height of the 30-mb surface varies about 4%, from a mean of 24 km in winter to 25 km in summer; while at 24 km the mean pressure varies by 12%, from 28.2 mb in winter to 31.8 mb in summer. Hence, the conversion

of mixing-ratio measurements from pressure surface to height introduces less error than would the conversion from heights to pressure surfaces.

However, this reverse conversion was required to determine the frostpoints corresponding to the mixing ratios of the two University of Denver flights, the molecular sieve, and the vapor trap. Since these data had been smoothed originally, and applied to layers rather than points, the error resulting from the use of Standard Atmosphere relations is negligible; more precise conversion, using atmospheric conditions prevailing at the times of the various flights, was possible but not worth while. Future determinations of stratospheric moisture would be of much greater utility if expressed in terms of both pressure and height.

All the ascents except the JMA, MRF, BRL, and U of D frostpoint soundings had been smoothed by the original investigators. The JMA, MRF, and Ft. Monmouth ascents were sufficiently regular that they required no smoothing. The U of D frostpoint ascent was smoothed by plotting the mixing ratio at every 1 km interval. The Aberdeen ascent was deliberately left unsmoothed to illustrate the "layering" effect that is often a feature of stratospheric hygrometric ascents. Such layers may be real or may be caused by "over-control"; when they do occur, the layers are found at different heights with time so that in a mean sounding they would be averaged out. The Aberdeen sounding was subsequently smoothed by eye.

The nonsystematic soundings could not be tested for bias. In several cases nothing other than mixing ratio and height, or pressure, was measured. This provided no basis for comparison with climatic records. Testing a single ascent for bias would be virtually meaningless. Thus the nonsystematic soundings were used in the hope they were representative.

8. RESULTS

8.1 Mixing Ratio

Troposhperic portions of the mixing-ratio profile, shown in Figure 3, were obtained as discussed in Section 6. For the stratospheric portion, mixing

ratios from each selected ascent were extracted at the 9-, 11-, 14-, 17-, 20-, 26-, 29-, and 31-km levels, and combined into six mixing ratios for each of these nine levels (when available):

a. The mean of the three NRL ascents
b. The mean of the two BRL ascents
c. The U of D spectroscopic ascent
d. The U of D hygrometric ascent
e. The JMA values
f. The MRF values.

These values are shown in Figure 3, together with the mean mixing ratio for the vapor trap at 27.5 km, the average height at which the samples were taken, and the equivalent molecular-sieve data. An arithmetic average value for each level was computed and plotted, giving equal weight to each of these six mixing-ratio values. Such weighting is purely subjective, admittedly. Assigning equal weights to, say, the MRF data (mean of nearly 400 ascents) and to a single U of D sounding does not imply that the U of D sounding is considered superior to the MRF ascents, nor that the soundings of any group are superior to those of any other group. The object of this study was reference atmosphere for moisture which theoretically should integrate time and space. Assigning equal weights appeared to yield results that would best approximate the true profiles. Only time will prove or disprove the validity of this personal opinion.

The smooth curve fitted to the average value at each of the nine levels (Figure 3) is considered to represent the average stratospheric mid-latitude mixing-ratio profile. Almost all the individual mixing-ratio measurements, of which averages are shown in Figure 3, lie within one order of magnitude of the mean curve (as shown there). Until more observations of known reliability are available, this interval may be considered to cover the range of usual variation of the mixing ratio -- including perhaps 90 percent of all values in middle latitudes. (Since the frequency distribution of mixing ratios is quite skewed, estimates of standard deviation are of little utility).

The mixing-ratio profile shows an almost logarithmic decrease with height from the surface to about 7 km; thence, a very steep moisture gradient to 9 km. From 9 km the mixing ratio decreases less rapidly to 14 km, then is almost constant to 17 km, reaching its minimum value in this layer. From 17 to 31 km, the mixing ratio increases logarithmically with height.

Based on the MRF data, Roach (1961)[23] suggested that up to 15 km the mixing ratio varies with the fourth power of the pressure: $w = a P^4$. A best-fitting straight line to the values shown in Figure 3, instead of the curve actually presented, has an exponent of 3.5, rather than 4, but Roach's suggestion may be useful as a rough approximation.

The most questionable part of the profile below 11 km is the layer between 7 and 9 km, for which no reliable data were available. Conventional radiosondes usually stop recording humidity even below 7 km; at 5 and 6 km they are notoriously inaccurate. Some investigators do not consider their frostpoint hygrometers reliable in layers with a combination of fast ascent and steep water-vapor gradient, such as prevail in this layer.

8.2 Dewpoint-Frostpoint

The dewpoint-frostpoint profile (Figure 4) was derived in a manner similar to that for the mixing ratio. In the troposphere, values used are the Fukuoka - Washington averages, discussed in a previous Section. In the stratosphere, all the observations used had been reported in terms of frostpoint as well as mixing ratio, except the two University of Denver flights, using the molecular sieve and the vapor trap; for these frostpoints were obtained from the reported mixing ratios, using standard atmosphere pressures for the indicated heights. Each individual or mean sounding was then plotted as dewpoint - frostpoint against height, and values extracted at 3 - km intervals shown in Figure 4. A smooth curve was then drawn through the means computed for the six (or fewer) values at each level, and values extracted for Table 4.

At all levels, the dewpoints are colder than the Standard Atmosphere temperature (also shown in Figure 4). The stratospheric mixing-ratio and frostpoint profiles are not quite equivalent, because some frostpoints were approximated whereas all mixing ratio values had been given directly.

Also, the exact relation between dewpoint and mixing ratio at any given pressure is not linear: a mean dewpoint at a given pressure computed from the mean mixing ratio will be warmer than the average of individual dewpoints. Thus the derived mean mixing-ratio profile could not be manipulated to yield an accurate equivalent mean dewpoint profile.

8.3 Other Measurements

The mean annual relative humidity profile from the surface to 7 km was derived in a conventional manner, using available data sources (Ratner 1957). Annual relative humidity data for the climatic variety of mid-latitudes were weighted and averaged to obtain representative values (Table 4).

Above 7 km, many of the selected stratospheric humidity ascents did not have concurrent temperature and moisture data from which the relative humidity could be obtained or even estimated. An estimation of the average annual relative humidity at 2-km intervals from 8 to 31 km was obtained from the average frostpoints (to the nearest whole degree) given in Table 4, using standard atmosphere temperatures for the same elevations. The relative humidity thus computed underestimates the true relative humidity since, at any given temperature the rate of change in relative humidity decreases with increasing temperature-dewpoint depression, so humidities from means are lower than mean humidities. In addition, relative humidity was also computed from the mean mixing ratio and corresponding Standard Atmosphere conditions.

Furthermore, the dewpoint-frostpoint corresponding to the mean mixing ratios, and the mixing ratios corresponding to the mean dewpoint-frostpoint values, were computed, again under Standard Atmosphere conditions. Finally, precipitable water, absolute humidity (vapor density), and vapor pressure were computed from each of the independently determined profiles of mixing ratio and dewpoint-frostpoint.

All these supplemental data, obtained by the appropriate formulas, are given in Table 4, together with explanation of the method of calculation. Asterisks indicate the values recommended for general use ; these generally are values obtained most directly from one of the two independent profiles, without Standard Atmosphere assumptions.

9. SUMMARY AND CONCLUSIONS

Mean Annual vertical profiles to 31 km in middle latitudes of mixing ratio and dewpoint-frostpoint, obtained as independent means from

Table 4: Mean annual mixing ratio ($\bar{w}$) and dewpoint-frostpoint ($\bar{T}_d$, $\bar{T}_f$) in middle latitudes, to 31 km, based on available routine and experimental data considered reliable, with related quantities computed (where required) for conditions of Revised U. S. Standard Atmosphere, 1962.

HT	STANDARD ATMOSPHERE: BASIC			STANDARD ATMOSPHERE: DERIVED			TYPICAL MOISTURE CONTENT FROM: MEAN MIXING RATIO						TYPICAL MOISTURE CONTENT FROM: MEAN FROSTPOINT					
gp km	T C	P mb	ρ g/m^3	e_s µb	ρ_s mg/m^3	w_s ppm	* $\bar{w}$ ppm	e_v µb	ρ_v mg/m^3	U %	T_d C	* W µ	* $\bar{T}_f$ C	* e'_v µb	* ρ'_v mg/m^3	* U' %	w' ppm	W' µ
0	+15.0	1013	1225	17044	12830	10473	6150	10016	7534	59	+7	10410	+4	8129	6360	75	5192	8901
2	-2.0	795	1006	7055	5559	5526	3200	4090	3219	58	-5	4367	-9	3097	2541	62	2526	3450
4	-11.0	616	819	2644	2186	2669	1580	1565	1294	59	-17	1673	-22	1054	909	49	1110	1254
6	-24.0	472	660	883	768	1163	700	531	462	60	-29	568	-33	382	344	43	522	440
8	-37.0	356	525	257	236	449	270	154	142	60	-42	150	-46	99.6	95	39	181	106
10	-50.0	264	413	39.35	38.21	92	37	15.70	15.3	40	-57	22	-60	10.8	11	28	26	14
12	-56.5	193	311	17.22	17.25	55	17	5.27	5.3	31	-65	8	-69	3.03	3.22	18	10	6
14	-56.5	141	227	17.22	17.25	76	10	2.27	2.3	13	-71	4	-74	1.42	1.55	8	7	2
16	-56.5	103	165	17.22	17.25	104	9	1.49	1.5	9	-74	3	-77	.89	.98	5	6	2
18	-56.5	75.0	121	17.22	17.25	142	13	1.57	1.8	9	-73	3	-78	.76	.84	4	7	2
20	-56.5	54.7	88.0	17.22	17.25	196	18	1.58	1.6	9	-73	4	-77	.89	.98	5	11	2
22	-54.5	40.0	63.7	22.32	22.16	348	27	1.74	1.7	8	-73	4	-76	1.04	1.14	5	[illegible]	2
24	-52.5	29.3	46.3	28.80	28.32	616	38	1.79	1.8	6	-73	4	-75	1.22	1.33	4	[illegible]	3
26	-50.5	21.5	33.7	36.99	36.06	1070	58	2.01	2.0	5	-72	4	-74	1.43	1.55	4	46	3
28	-48.5	15.9	24.6	47.30	45.62	1854	86	2.19	2.1	5	-71	5	-73	1.66	1.80	4	73	4
30	-46.5	11.7	18.0	60.22	57.57	3198	128	2.41	2.3	4	-71	2	-72	1.94	2.08	3	116	4
31	-45.5	10.1	15.4	67.84	64.57	4193	150	2.43	2.3	4	-70	-	-71	2.25	2.41	3	157	-

Standard Atmosphere, from Revised U. S. Standard Atmosphere, 1962 ("RUSSA").

T, P, ρ: temperature (°C), pressure (mb), density of air (g/m^3) (assumed dry).

Pressure of water vapor, in microbars: 1 µb = 0.001 mb = 1 dyn/cm^2.

e_s: if saturated at ambient RUSSA temperature; from SMT 94 and 96.

e_v: having mixing ratio $\bar{w}$ at ambient RUSSA pressure; $e_v = \bar{w} P/0.622$.

* e'_v: having dewpoint $\bar{T}_d$ or frostpoint $\bar{T}_f$; from SMT 94 and 96.

Absolute humidity or vapor density or vapor concentration in mg/m^3 ($1 mg/m^3 = 0.001 g/m^3$).

ρ_s: If saturated at ambient RUSSA temperature and density, from SMT 108 and 109.

ρ_v: having mixing ratio $\bar{w}$ at ambient RUSSA pressure and density; $\rho_v = \rho\bar{w}$.

* ρ'_v: having dewpoint T_d or frostpoint T_f; from SMT 108 and 109.

Mixing ratio, ratio of mass of water vapor to that of dry air in mixture, in mg/kg, or parts per million.

w_s: if saturated at ambient RUSSA temperature and density; $w_s = \rho_s / \rho$.

* $\bar{w}$: estimated mean mid-latitude value, from available mixing ratio data considered reliable.

w': having dewpoint T_d or frostpoint T_f at RUSSA density; $w' = \rho'_v / \rho$.

Precipitable water, water vapor content of air in 2-km layer above indicated level, if condensed to liquid, in microns ($1 \mu = 0.000\,1$ cm $= 0.000\,1$ g/cm^2).

* W : $= (p_2 - p_1)\,\bar{w}/g$; $\bar{w}$ is mean mixing ratio between pressures p_1 and p_2 2 km apart (RUSSA); $g = 980$ cm/sec^2.

W' : $\overline{\rho'_v}h$, where H is layer thickness in meters, $= \rho'_v(Z_1) + \rho'_v(Z_1 + 2\text{ km})$.

Relative humidity, in percent.

U : ratio of pressures of water vapor in mixing ratio $\bar{w}$ and if saturated at RUSSA temperature; $U = e_v/e_s$.

* U': up to 6 km, weighted average of observed relative humidities;
above 6 km, $U' = e'_v/e_s$, for air having frostpoint T_f and RUSSA temperature.

Dewpoint and frostpoint temperature, in degrees Celsius.

T_d, T_f : from SMT 94 and 96, using e_w as derived from $\bar{w}$.

* T_d, T_f : estimated mean mid-latitude values, from available data expressed as dewpoints and frostpoints.

Notes

* indicates values recommended for general use; other values derived for comparison only.

SMT = Smithsonian Meteorological Tables, sixth revised edition, prepared by R. J. List, Washington 1951.

Saturation assumed with respect to plane surfaces of liquid water above -40°C, of ice below -40°C.

the same basic measurements of stratospheric moisture and routine tropospheric radiosonde observations, are presented in Figures 3 and 4 and Table 4. Neither profile can be obtained from the other: the non-linear relation between mixing ratio and condensation temperature (dewpoint - frostpoint) insures that the respective means, separately obtained, will not correspond.

From each of the basic profiles, other expressions for the moisture content of the atmosphere have been derived, using Standard Atmosphere conditions where required. The two sets of values of absolute humidity (vapor density), vapor pressure, precipitable water, and relative humidity differ, of course. Preferred values are indicated by asterisk. (Relative humidity up to 7 km was computed independently, from published radiosonde summaries).

The most reliable single element is the mixing ratio, because all the selected data were given in terms of mixing ratio and required no approximations, such as those used for the dewpoint - frostpoints. However, values derived from the dewpoint - frostpoint seem more reliable than those based on the mixing ratio, because fewer Standard Atmosphere assumptions are used. A small change in dewpoint corresponds to a large change in mixing ratio, especially at low dewpoint: the mean annual mixing ratio at 10 km is 37 ppm, while the mean frostpoint of -602 corresponds to a mixing ratio (at 264 mb) of 26 ppm.

The tentative moisture profiles presented herein undoubtedly will be revised and extended as the state-of-the-art advances. The large amount of subjectivity used in deriving the stratospheric portion of the moisture profiles makes revision especially desirable. Despite their deificiencies, these models may be used until expected revisions and extensions appear.

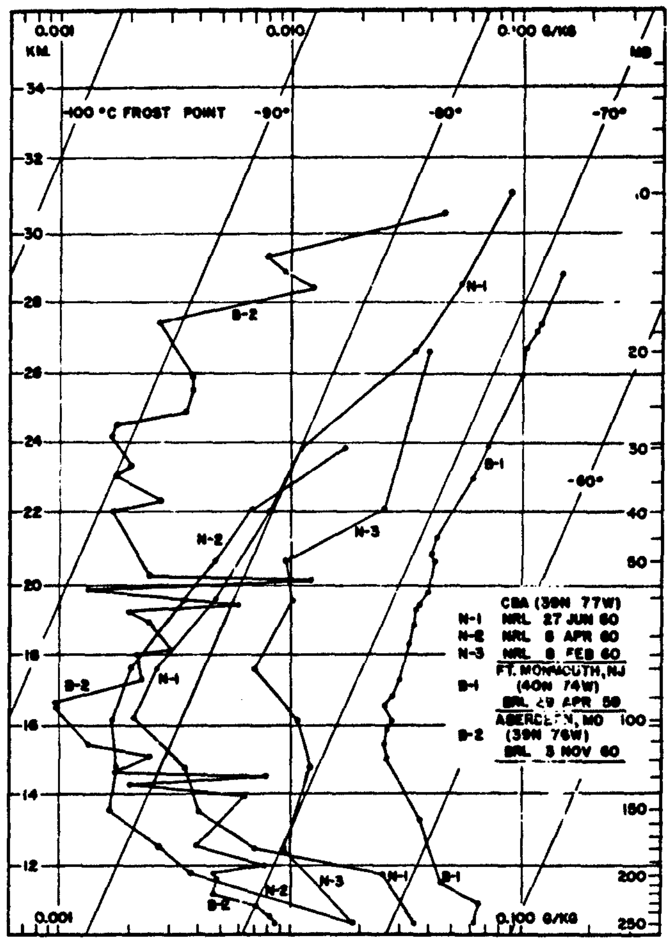
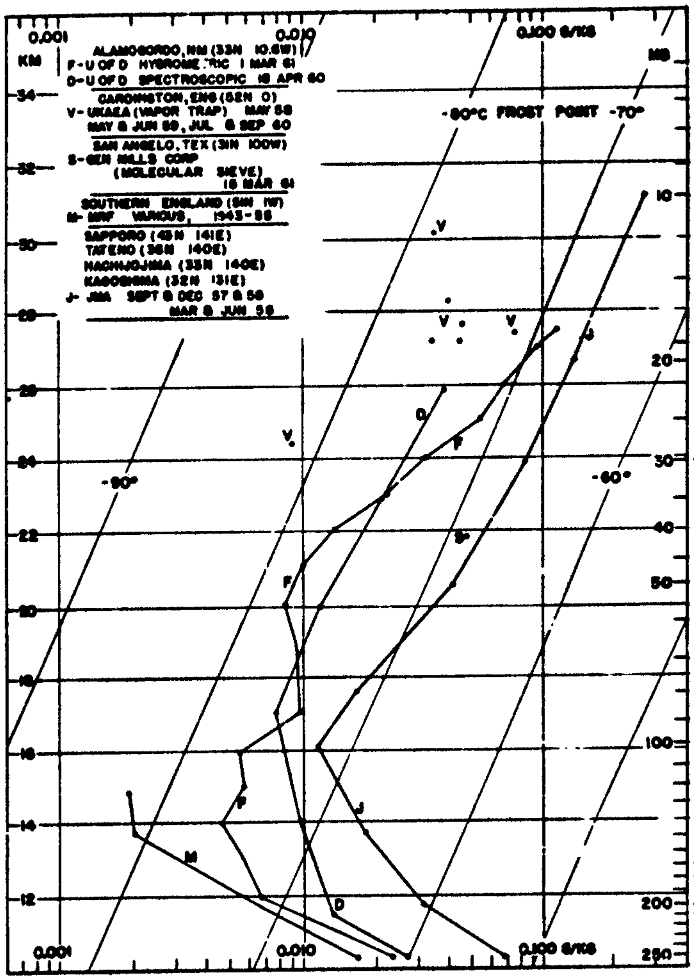

0.001
0.010
0.100 G/KG
KM.
MB
-100 °C FROST POINT
-90°
-80°
-70°
-60°
N-1
N-2
N-3
B-1
B-2
CBA (39N 77W)
N-1 NRL 27 JUN 60
N-2 NRL 6 APR 60
N-3 NRL 8 FEB 60
FT. MONMOUTH, NJ (40N 74W)
B-1 BRL 29 APR 59
ABERDEEN, MD (39N 76W)
B-2 BRL 3 NOV 60
0.100 G/KG

Figure 1



0.001
0.010
0.100 G/KG
KM
MB
ALAMOGORDO, NM (33N 10.6W)
F-U OF D HYGROMETRIC 1 MAR 61
D-U OF D SPECTROSCOPIC 18 APR 60
CARDINGTON, ENG (52N 0)
V-UKAEA (VAPOR TRAP) MAY 58
MAY & JUN 59, JUL & SEP 60
SAN ANGELO, TEX (31N 100W)
S-GEN MILLS CORP
(MOLECULAR SIEVE)
15 MAR 61
SOUTHERN ENGLAND (51N 1W)
M-MRF VARIOUS, 1943-55
SAPPORO (43N 141E)
TATENO (36N 140E)
HACHIJOJIMA (33N 140E)
KAGOSHIMA (32N 131E)
J-JMA SEPT & DEC 57 & 58
MAR & JUN 58
-80°C FROST POINT -70°
-90°
-60°
34
32
30
28
26
24
22
20
18
16
14
12
10
20
30
40
50
100
200
250

Figure 2

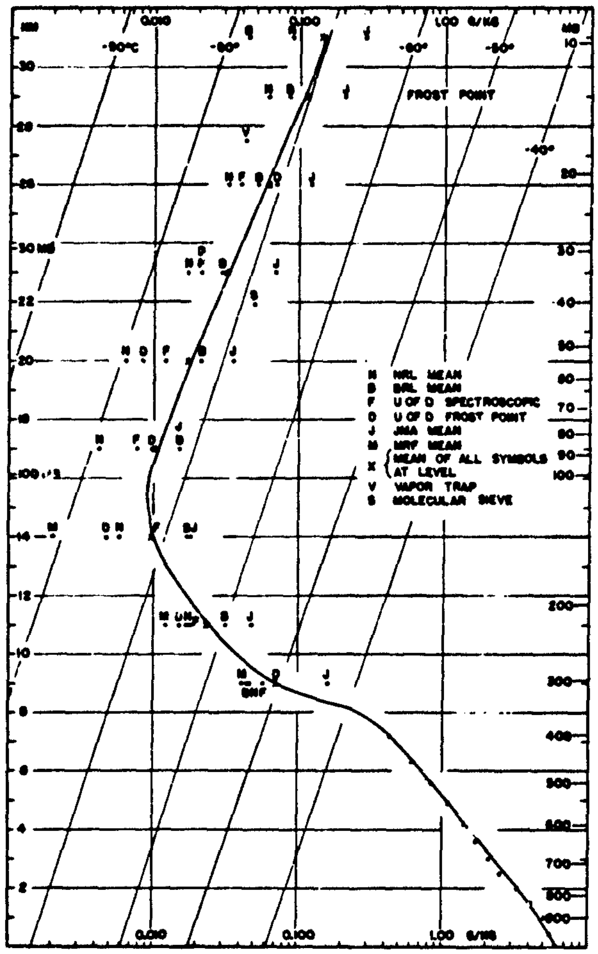

KM
MB
0.010
0.100
1.00 G/KG
-90°C
-80°
-60°
-50°
-40°
FROST POINT
30 MB
100
200
300
400
500
600
700
800
900
N NRL MEAN
B BRL MEAN
F U OF D SPECTROSCOPIC
D U OF D FROST POINT
J JMA MEAN
M MRF MEAN
X MEAN OF ALL SYMBOLS AT LEVEL
V VAPOR TRAP
S MOLECULAR SIEVE

Figure 3

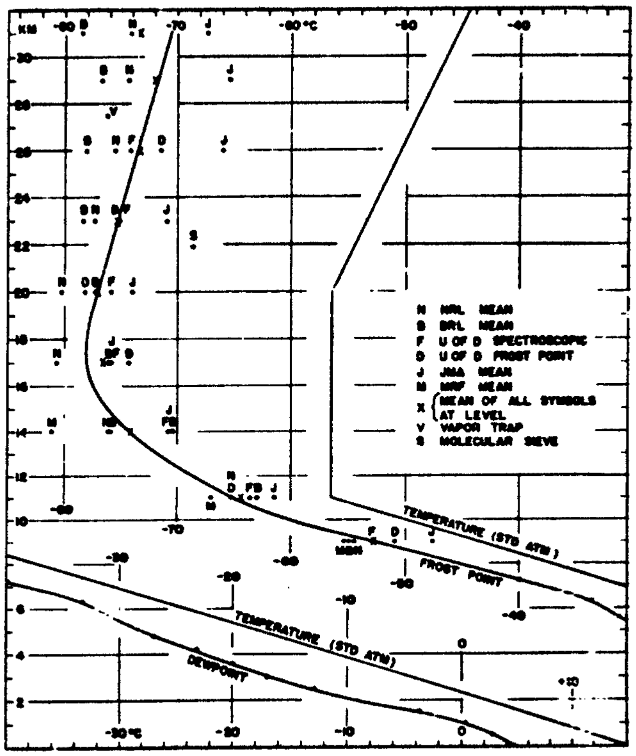

KM
-70
-60 °C
-50
-40
N NRL MEAN
B BRL MEAN
F U OF D SPECTROSCOPIC
D U OF D FROST POINT
J JMA MEAN
M MRF MEAN
X MEAN OF ALL SYMBOLS AT LEVEL
V VAPOR TRAP
S MOLECULAR SIEVE
TEMPERATURE (STD ATM)
FROST POINT
TEMPERATURE (STD ATM)
DEWPOINT
-30 °C
-20
-10
0

Figure 4

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